HEAVY QUARKS AS PARTONS

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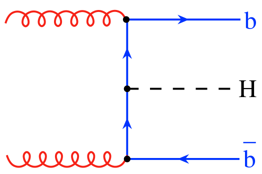
SUMMARY

- HEAVY QUARKS IN THE INITIAL STATE
  - 4FS VS 5FS
  - APPROXIMATE AND PHEONOMENOLOGICAL APPROACHES
- THE FONLL METHOD
  - MATCHING RENORMALIZATION SCHEMES
  - FONLL FOR DIS
- PARAMETRIZED HEAVY QUARKS
  - INITIAL HEAVY QUARKS PDFS
  - PARAMETRIZED CHARM: PHENOMENOLOGY
- HIGGS PRODUCTION IN BOTTOM FUSION
  - "SANTANDER MATCHING"
  - FONLL RESULTS: CONSTANTS VS LOGS
  - MATCHING SCALES AND $\bar{b}bZ$
- PARAMETRIZED B
  - A MASSIVE b SCHEME
  - $b\bar{b}H$ AND THE ROLE OF THE b PDF

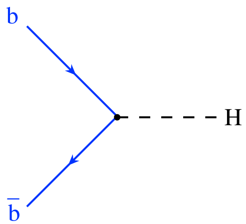
AN OLD PROBLEM: MASSIVE QUARK SCHEMES

EXAMPLE: $b\bar{b} \to H$

LO 4 FLAVORS



LO 5 FLAVORS



- 4FS $\Rightarrow$ MASSIVE B, NO b IN DGLAP EVOLUTION AND β FUNCTION
- 5FS $\Rightarrow$ Mb IN DGLAP EVOLUTION AND β FUNCTION BUT b MASS NEGLECTED

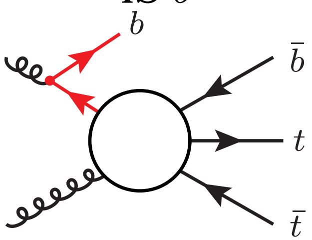
SHOWERING Bs

$t\bar{t} + b$-jet

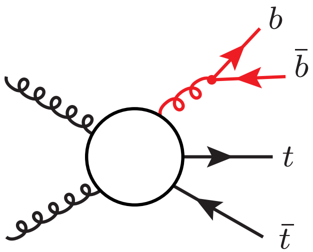
(Jezo, Lindert, Moretti, Pozzorini, 2018)

- IN 5FS, B-JET MOSTLY DRIVEN BY PS, NEGLIGIBLE MATRIX ELEMENT
- IN 4FS, DOMINANT CONTRIBUTION FROM FS GLUON SPLIITING
- NEW POWHEG GENERATOR: 4FS+NLOPS $\Rightarrow$ PS EFFECTS MODERATE, $\sim 10\%$ AT LARGE p_T FOR $t\bar{t}b\bar{b}$.

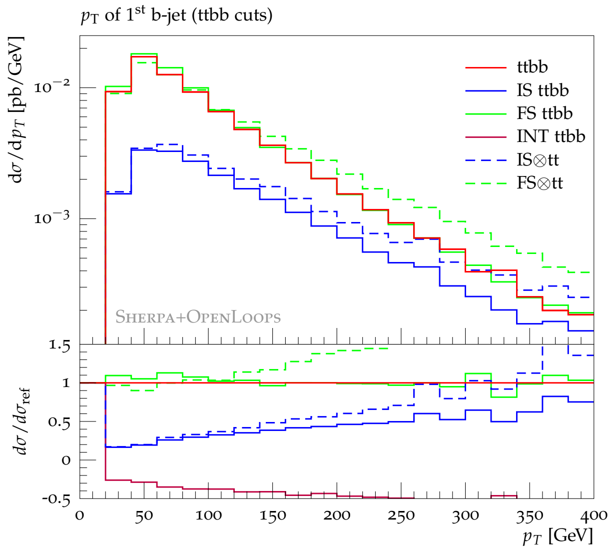
IS b



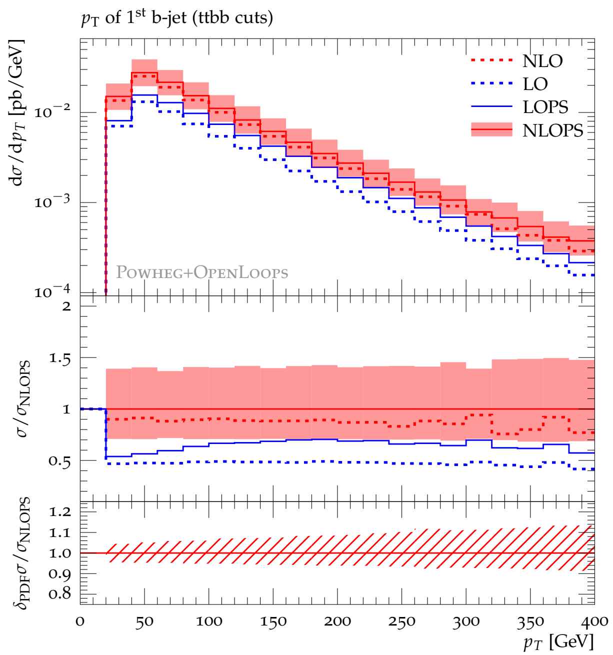
FS b



p_T OF b-JET: IS VS FS



p_T OF b-JET: PERT. ORDERS



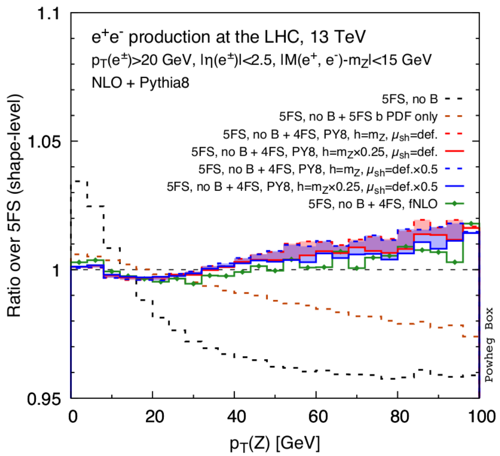
APPROXIMATE 4FS-5FS PS MATCHING

W Z production and the W mass

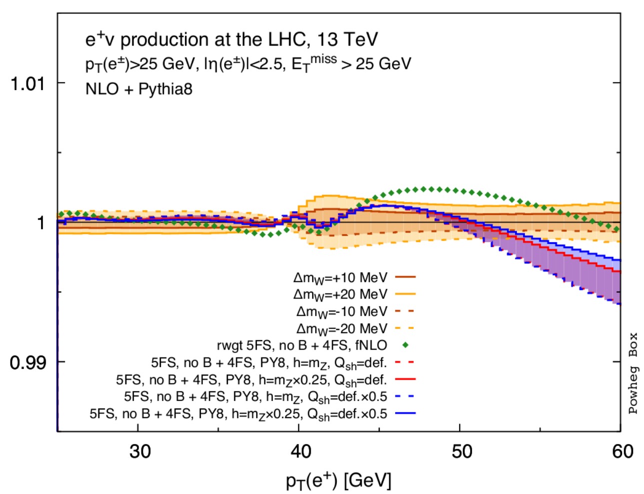
(Bagnaschi, Maltoni, Vicini, Zaro, 2018)

- MATCH 4FS WITH MASS EFFECTS TO 5FS PS & SUBTRACT (VETO) ALL FINAL STATE bS
- TUNE MATCHING SCHEME TO Z PRODUCTION
- USE FOR W PRODUCTION $\Rightarrow \Delta M_W \sim 5$ GeV EFFECT ON M_W DETERMINATION

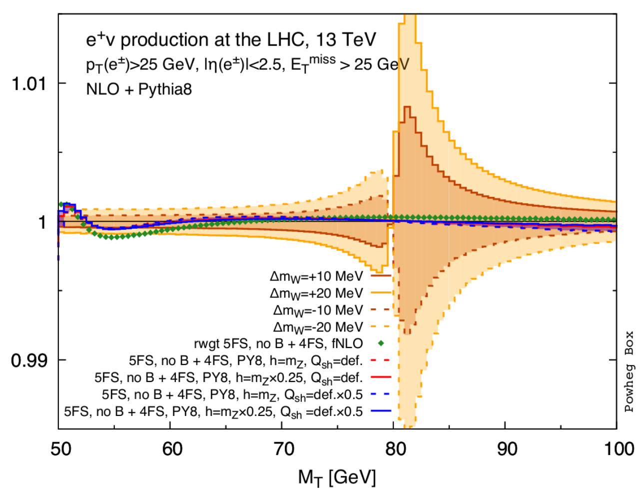
Z: IMPROVED TUNES VS 5FS



p_T LEPTON



M_W TEMPLATES VS. IMPROVED TUNES m_t



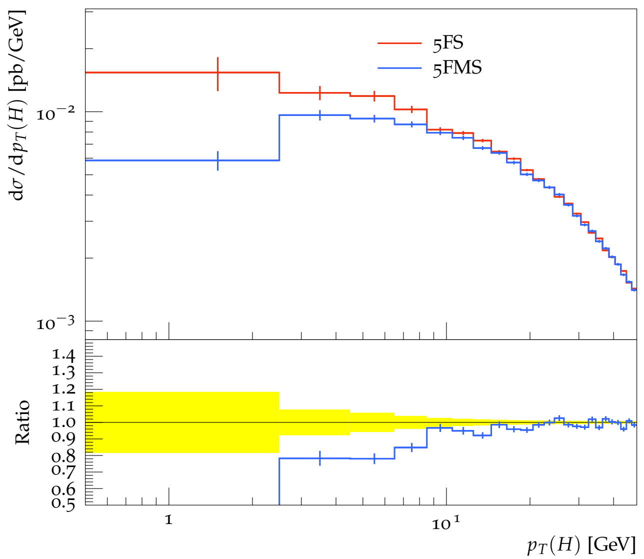
MASSIVE EVOLUTION

(Krauss, Napoletano, 2018)

- MASSIVE FIVE-FLAVOR SCHEME: MASS INCLUDED IN SPLITTING KERNELS
- +: CAN BE IMPLEMENTED IN PS (SHERPA AVAILABLE)
- +: MASSIVE CORRECTIONS EXPONENTIATED
- -: ONLY (UNIVERSAL) SUBSET OF FONLL TERMS INCLUDED
- FIRST APPLICATION TO $Z+b$ PRODUCTION: Figueroa et al, 2018

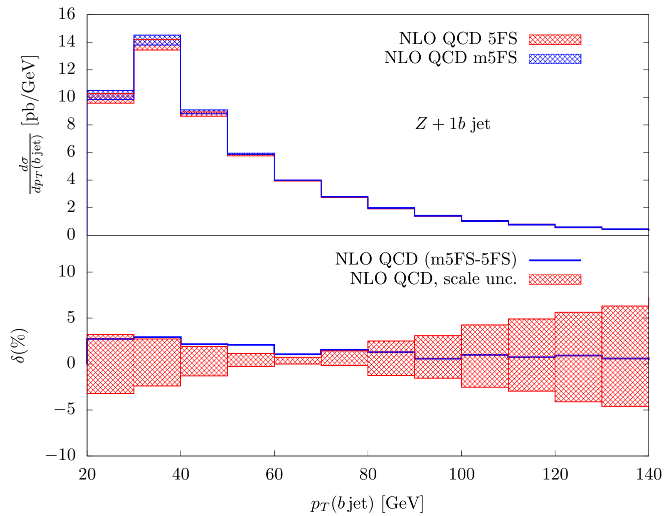
5FS VS MFS

$b\bar{b} \to H$



(Krauss, Napoletano, 2018)

Z+B: p_t SPECTRUM OF B JET



(Figueroa, Honeywell, Quackenbusch, Reina, Reuschle, Wackeroth, 2018)

FONLL

- ORIGINALLY DEVELOPED TO EXPLAIN THE b p_t SPECTRUM (Cacciari, Greco, Nason, 1998)
- RESUM $\ln \frac{p_t}{m_b}$ BUT RETAIN $\frac{m_b}{p_t}$ POWER CORRECTIONS

BASIC IDEA:
THE PROBLEM

- TYPICAL GAUGE SELF-ENERGY $\Pi(q^2)$DEPENDS ON $\ln M^2 = \ln(m^2 + x(1-x)q^2) \Rightarrow$

  $$\beta = \frac{d}{d\ln q^2} \ln M^2 \sim \begin{cases} 1 & \text{IF } q^2 \gg m^2 \\ O(\frac{q^2}{m^2}) & \text{IF } m^2 \gg q^2 L \end{cases}$$

  - $\overline{\text{MS}}$ SCHEME $\rightarrow$ ZERO-MASS SUBTRACTION, $n_f = 6$ AT ALL SCALES
  - DECOUPLING SCHEME $\rightarrow$ HEAVY-FLAVOR GRAPHS SUBTRACTED AT ZERO MOMENTUM, n_f VARIABLE

THE SOLUTION

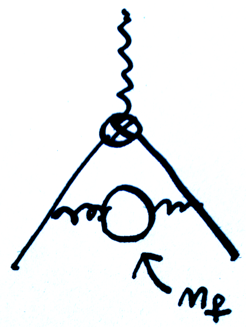
- PERFORM THE COMPUTATION IN BOTH SCHEMES: $\overline{\text{MS}}$ OR " MASSLESS" $(n_f + 1)$ & "DECOUPLING" OR "MASSIVE" (n_f)
- RE-EXPRESS MASSIVE RESULT IN TERMS OF MASSLESS PDFs & α_s
- COMBINE BOTH & SUBTRACT DOUBLE-COUNTING

FONLL

HOW DOES IT WORK?

MATCHING

$$f_i^{(n_f+1)}(x,m^2) = K_{ij}(\alpha_s)\otimes f_j^{(n_f)}(x,m^2) = f_i^{(n_f)}(x,m^2) + \alpha_s K_{ij}^{(1)}\otimes f_j^{(n_f)}(x,m^2) + \dots$$



- K_{ij} FOR $i = h, q, \bar{q}, g$, $j = q\bar{q}, g$ AT $O(\alpha_s^2)$ $\Leftrightarrow$ TWO-LOOP NORMALIZATION MISMATCH BETWEEN Q AND G OPERATOR
- K_{hh} STARTS AT $O(\alpha_s)$ (h IN n_f?? MORE LATER)

RE-EXPRESSING

- AT ANY OTHER SCALE, LHS EVOLVES WITH (n_f+1) & RHS WITH n_f ALTARELLI-PARISI: e.g. GLUON

$$f_g^{(n_f)}(x,Q^2) = \left[1 + \frac{\alpha_s}{2\pi}\frac{2T_R}{3}\ln\frac{Q^2}{m_h^2}\right] f_g^{(n_f+1)}(x,Q^2)$$

COMBINING

$$\sigma^{\rm FONLL} = \sigma^{(\rm n_f)} + \sigma^d;\quad \sigma^d = \sigma^{(\rm n_f+1)} - \sigma^{(\rm n_f,0)} \text{ with } \lim_{m_h\to 0}\sigma^{(\rm n_f)} - \sigma^{(\rm n_f,0)} = 0$$

$$\sigma^{(n_f)} = B_{ij}(\alpha_s^{(n_f+1)})\otimes f_i^{(n_f+1)}\otimes f_i^{(n_f+1)};$$

$$B_{ij}(\alpha_s^{(n_f+1)})\otimes f_i^{(n_f+1)}\otimes f_i^{(n_f+1)} = \hat\sigma_{ij}(\alpha_s^{(n_f)})\otimes f_i^{(n_f)}\otimes f_i^{(n_f)}\Rightarrow$$

$$B_{ij}(\alpha_s^{(n_f+1)}) = \hat\sigma_{ab}K_{ai}^{-1}K_{bj}^{-1}$$

FONLL

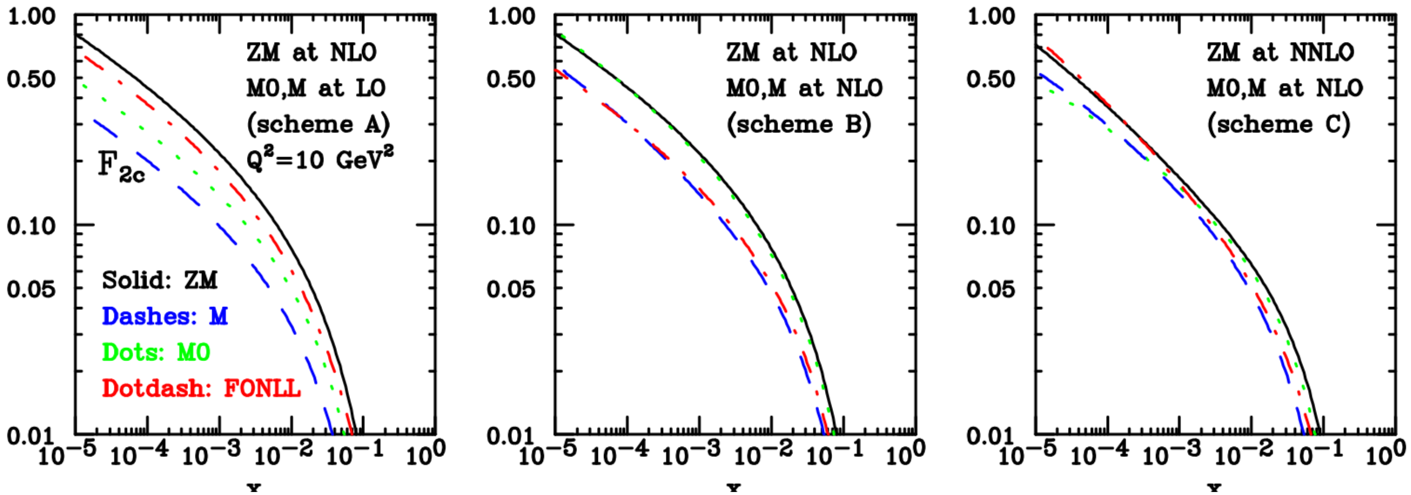
$$\sigma^{(n_f)} = B_{ij}(\alpha_s^{(n_f+1)}) \otimes f_i^{(n_f+1)} \otimes f_i^{(n_f+1)};$$
$$B_{ij}(\alpha_s^{(n_f+1)}) \otimes f_i^{(n_f+1)} \otimes f_i^{(n_f+1)} = \hat{\sigma}_{ij}(\alpha_s^{(n_f)}) \otimes f_i^{(n_f)} \otimes f_i^{(n_f)}$$

- THE MASSIVE $(n_f) \Rightarrow m_h$ DEPENDENCE RETAINED, MASSLESS $(n_f+1) \Rightarrow$ MASS LOGS RESUMMED
- MASSIVE (n_f) AND MASSLESS (n_f+1) CAN BE PERFORMED AT DIFFERENT ORDERS & COMBINED
- COMPLEMENTARY VIEWS:
  - $\sigma^{(n_f+1)}$: ALL ORDERS IN $\alpha_s^{(n_f+1)}$ TO WHICH $\sigma^{(n_f+1)}$ IS KNOWN REPLACED BY THEIR MASSIVE COUNTERPART
  - MASS LOGS REMOVED FROM $f_i^{(n_f+1)}$, USED IN THE COMPUTATION OF $\sigma^{(n_f)}$
- $\sigma^{(d)}$ SUBLEADING WRT BOTH MASSLESS AND MASSIVE
- $\sigma^{(d)}$ IS JUNK $\Rightarrow$ DAMPING

FONLL

- DEVELOPED FOR HADROPRODUCTION & ELECTROPRODUCTION (S.F., Laenen, Nason, Rojo, 2010)
- NECESSARY FOR DEEP-INELASTIC CHARM PRODUCTION
- ROUTINELY USED IN PDF FITS (SINCE NNPDF 2.1)

F_2^c at $Q^2 = 10\ \mathrm{GeV}^2$



- FONLL-A: MASSIVE $O(\alpha_s)$ (LO); MASSLESS $O(\alpha_s)$ COEFF. FCTN, & SPLITTING FCTN (NLO)
- FONLL-B: MASSIVE $O(\alpha^2)$ (NLO); MASSLESS $O(\alpha_s)$ COEFF. FCTN, & SPLITTING FCTN (NLO)
- FONLL-C: MASSIVE $O(\alpha_s^2)$ (NLO); MASSLESS $O(\alpha_s^2)$ COEFF. FCTN, & SPLITTING FCN (NNLO)

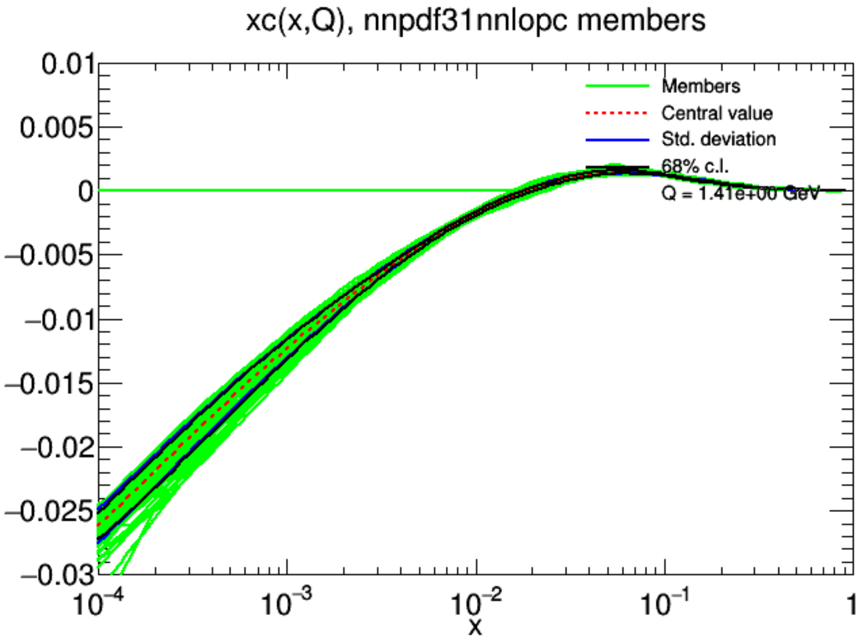
THE HEAVY QUARK PDF

THE CASE OF CHARM

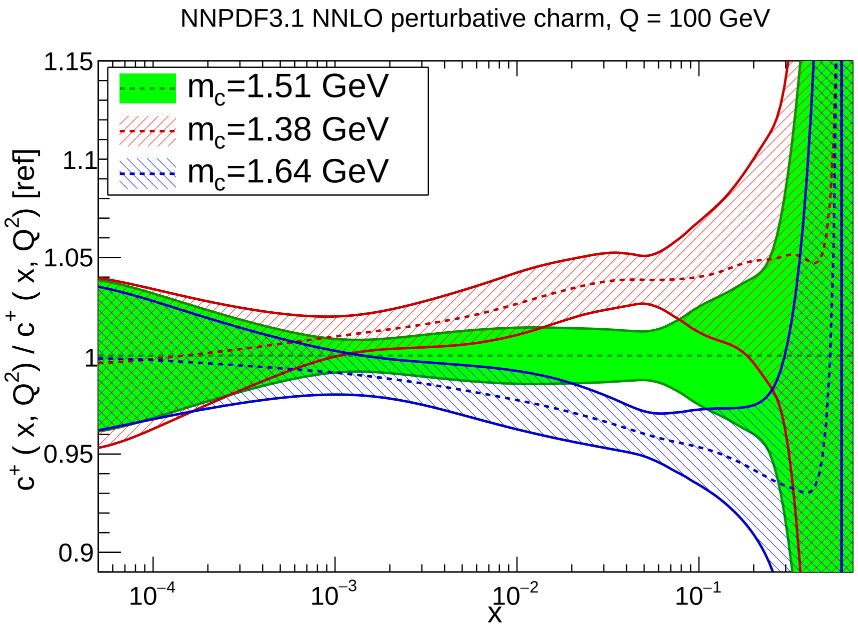
- IN STANDARD FONLL, f_h DETERMINED FROM MATCHING CONDITION
- AT $O(\alpha_s)$, $f_h(m_h^2) = 0$; NONTRIVIAL AT $O(\alpha_s^2)$
- BEST-FIT f_c DEPENDS STRONGLY ON m_c; SMALL UNCERTAINTY (DRIVEN BY GLUON)

NNLO PERTURBATIVE CHARM

AT $Q = m_c$



DEPENDENCE ON m_c



FONLL WITH PARAMETRIZED HEAVY QUARK

$$f_i^{(n_f+1)}(x,m^2) = K_{ij}(\alpha_s) \otimes f_j^{(n_f)}(x,m^2)$$

- MASSIVE-SCHEME f_h DOES NOT EVOLVE
- SQUARE MATCHING MATRIX
- WHEN RE-EXPRESSING, EVOLUTION REMOVED UP TO FIXED-ORDER

$$f_h^{(\mathrm{n_f},\,\mathrm{NLO})}(x,Q^2) = \sum_i \left[1 - \frac{\alpha_s}{2\pi} P_{hi} \ln \frac{Q^2}{m_h^2}\right] \otimes f_i^{(\mathrm{n_f}+1,\,\mathrm{NLO})}(x,Q^2)$$

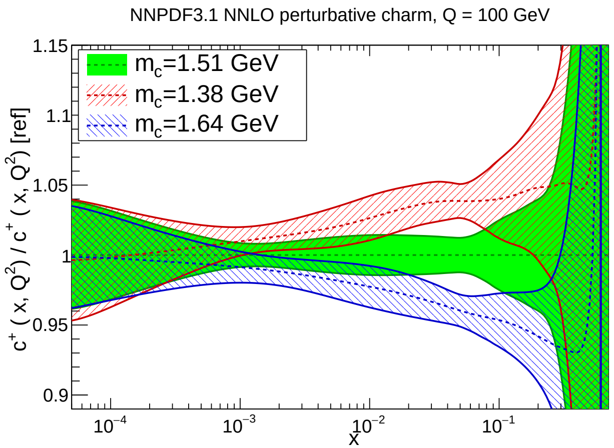
- THE "DIFFERENCE" TERM MOW VANISHES!!
- FONLL $\Rightarrow$ MASSIVE PARTONIC XSECT WITH MASSLESS PARTONS

$$F^{\mathrm{FONLL}}(x,Q^2) = C_i^{(\mathrm{n_f})} \otimes K_{ij}^{-1} \otimes f_j^{(\mathrm{n_f}+1)} + F^d(x,Q^2);$$
$$F^d = \left(C_j^{(\mathrm{n_f}+1)} - C_i^{(\mathrm{n_f},\,0)} \otimes K_{ij}^{-1}\right) \otimes f_j^{(\mathrm{n_f}+1)} = 0$$

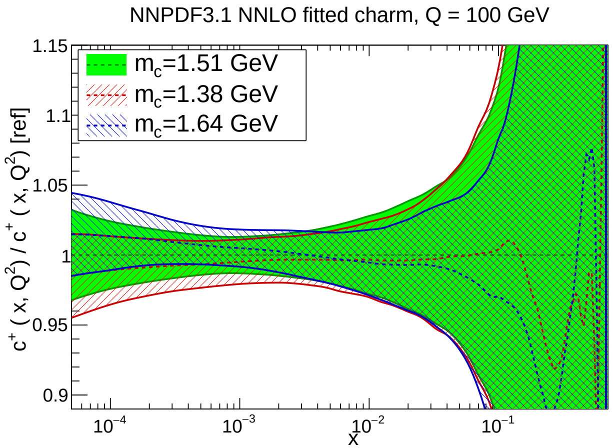
PARAMETRIZED CHARM: PHENOMENOLOGY
THE CHARM PDF

- CHARM SHOULD NOT DEPEND STRONGLY ON CHARM MASS

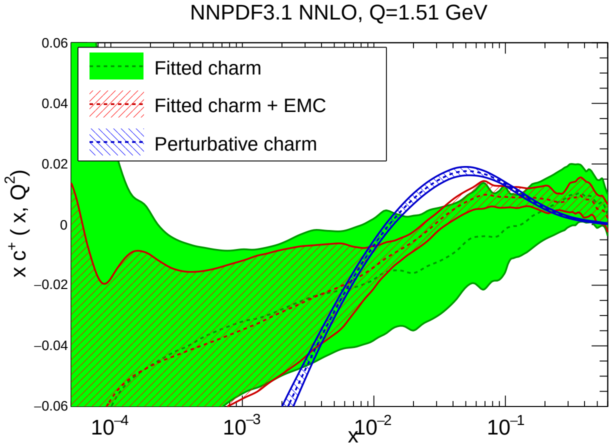
PERTURBATIVE CHARM VS m_c



FITTED CHARM VS m_c



FITTED VS. PERTURBATIVE CHARM



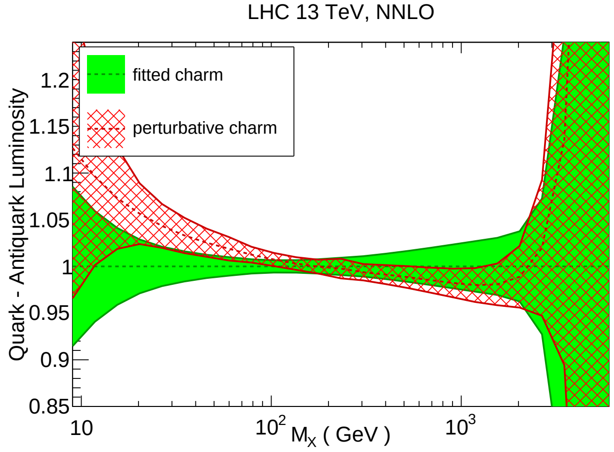
- ITS SHAPE SHOULD NOT BE DETERMINED BY FIRST-ORDER MATCHING (NO HIGHER NONTRIVIAL ORDERS KNOWN)
- MIGHT EVEN HAVE A NONPERTURBATIVE COMPONENT

FITTED VS. PERTURBATIVE:
SUPPRESSED AT MEDIUM-SMALL x,
ENHANCED AT VERY SMALL, VERY LARGE x

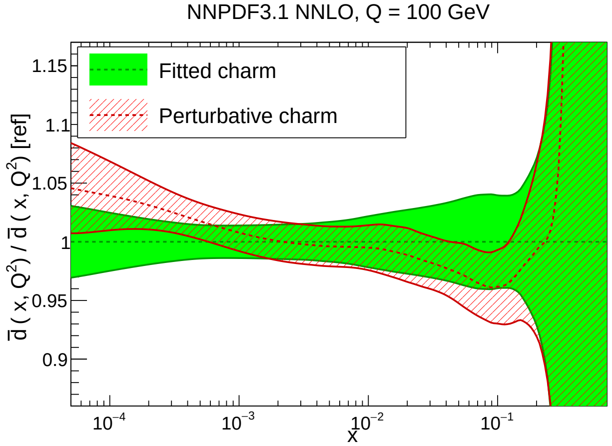
PARAMETRIZED CHARM: PHENOMENOLOGY
IMPACT ON LIGHT QUARK PDFS

FITTED VS. PERTURBATIVE CHARM

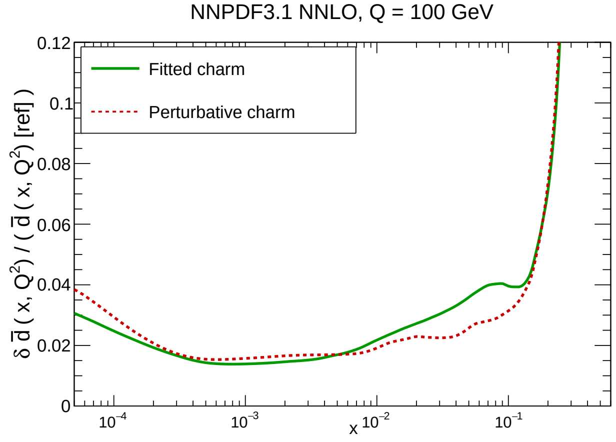
QQBAR LUMI



ANTIDOWN PDF



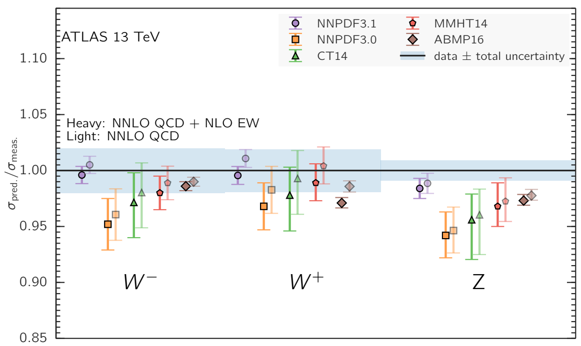
ANTIDOWN PDF UNCERTAINTY



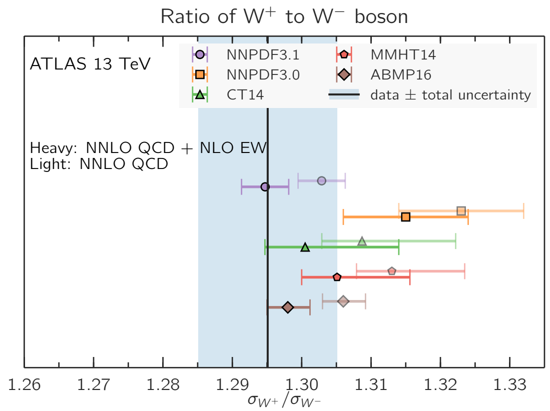
- QUARK LUMI AFFECTED BECAUSE OF CHARM SUPPRESSION AT MEDIUM-x
- FLAVOR DECOMPOSITION ALTERED
- UNCERTAINTIES ON LIGHT QUARKS NOT SIGNIFICANTLY INCREASED
- AGREEMENT OF 13TeV W,Z PREDICTED CROSS-SECTIONS IMPROVES!

PARAMETRIZED CHARM: PHENOMENOLOGY
IMPACT ON STANDARD CANDLES

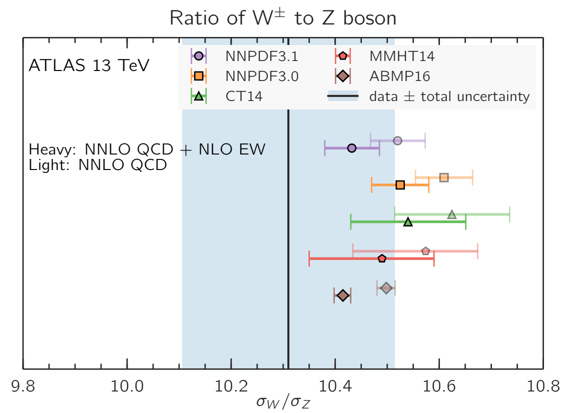
Drell-Yan xsects



W^+/W^- xsect ratio



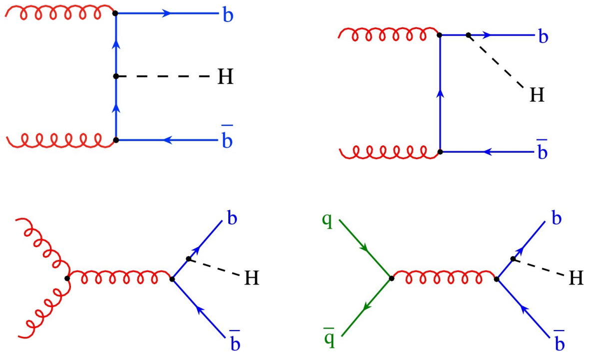
W/Z xsect ratio



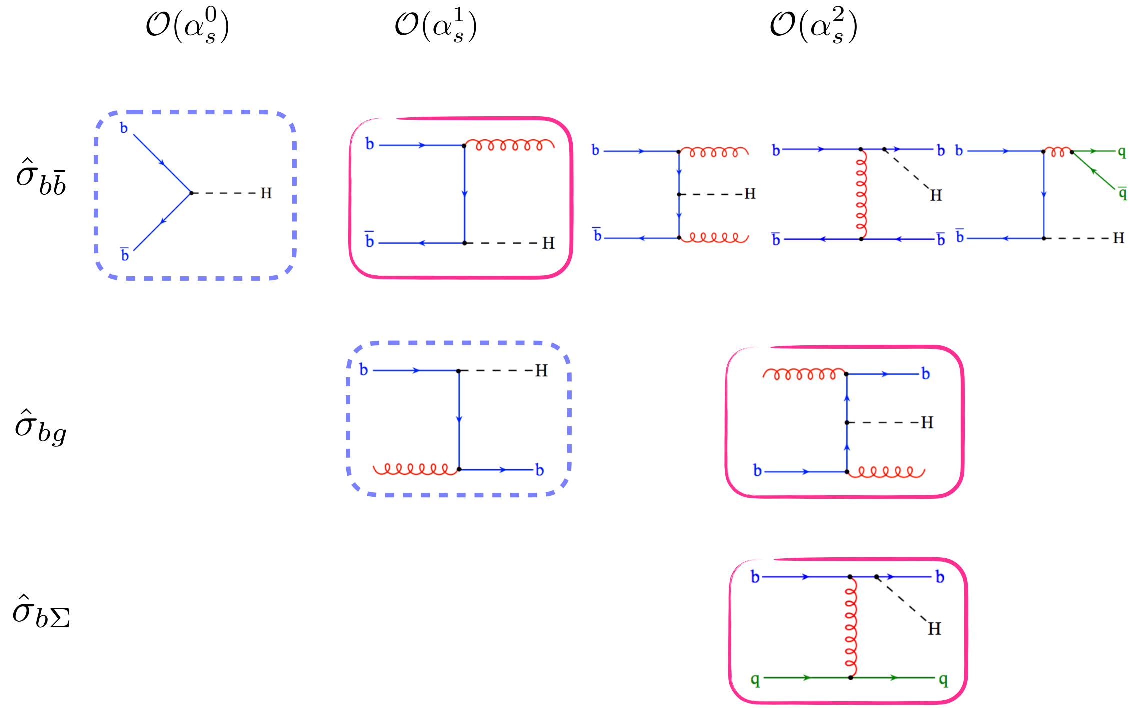
- W, Z cross-sections at 13 TeV in perfect agreement with data thanks to fitted charm!

HADROPRODUCTION:
HIGGS IN BOTTOM FUSION

MASSIVE LO

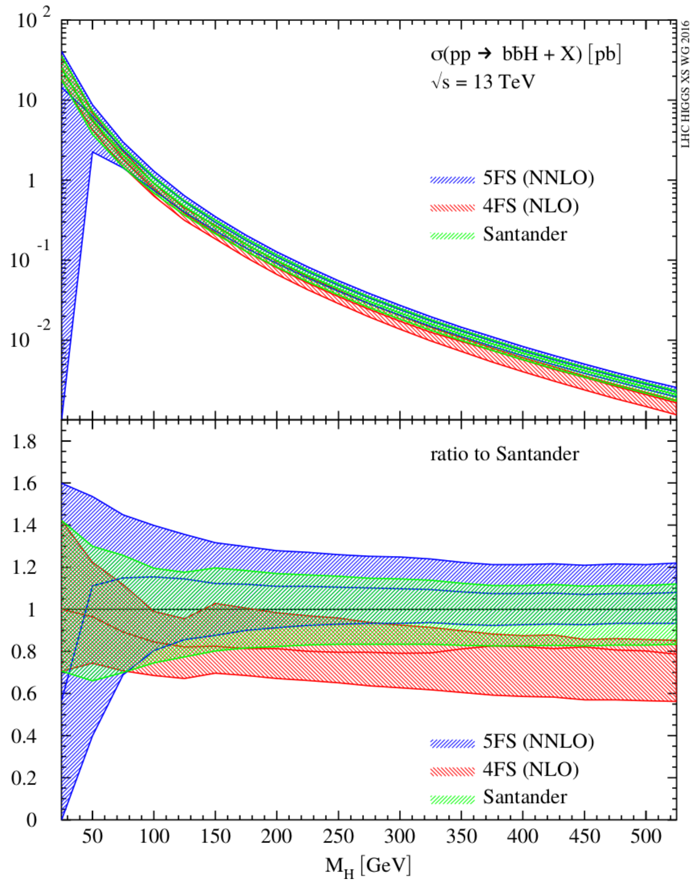


MASSLESS NNLO



- FONLL-A: MASSIVE $O(\alpha_s^2)$ (LO); MASSLESS $O(\alpha_s^2)$ COEFF. FCTN, & SPLITTING FCTN (NNLO)
- FONLL-B: MASSIVE $O(\alpha^3)$ (NLO); MASSLESS $O(\alpha_s^2)$ COEFF. FCTN, & SPLITTING FCTN (NNLO)
- FONLL-C: MASSIVE $O(\alpha^3)$ (NLO); MASSLESS $O(\alpha_s^3)$ COEFF. FCTN, & SPLITTING FCTN (NNLO) $\Rightarrow$ COEFFICIENT FUNCTION RECENTLY COMPUTED (Duhr, Dulat, Mistlberger, 2019)

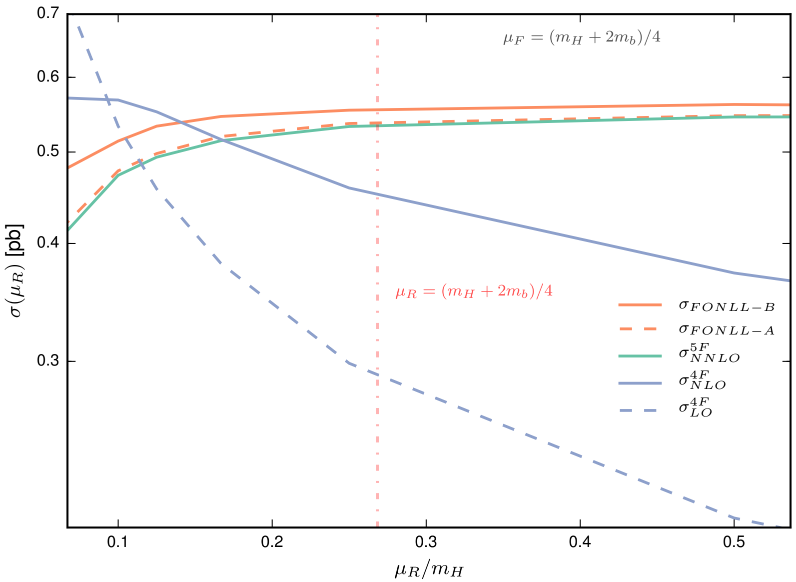
HIGGS IN BOTTOM FUSION
PROBLEMS

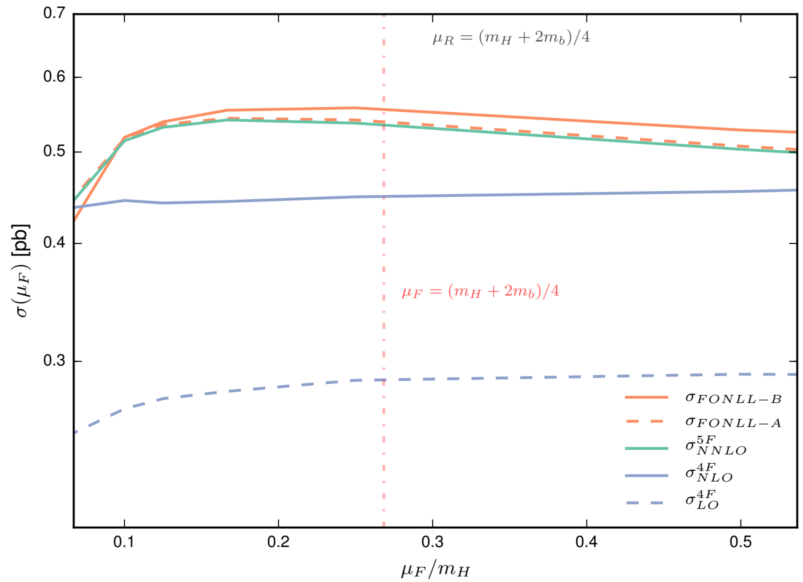


(HXSWG, YR4, 2017, Spira, Wiesemann et al.)

- 4FS ("MASSIVE") AND 5FS ("MASSLESS") GIVE RATHER DIFFERENT RESULTS
- DISCREPANCY ALLEVIATED WITH LOWER RENORMALIZATION SCALE $\Rightarrow$ ARGUED THAT $\mu_3 = \frac{m_h+2m_b}{4}$ APPROPRIATE BASED ON TYPICAL SCALE OF COLLINEAR LOGS (Maltoni, Ridolfi, Ubiali, 2012, + Lim, 2016): TYPICALLY $Q \sim p_t^{\max}/2$
- "SANTANDER" MATCHING: $\sigma = \frac{\sigma^{(4)}+w\sigma^{(5)}}{1+w}$, $w = \ln\frac{m_h}{m_b} - 2 \approx 1.2$

HIGGS IN BOTTOM FUSION
FONLL

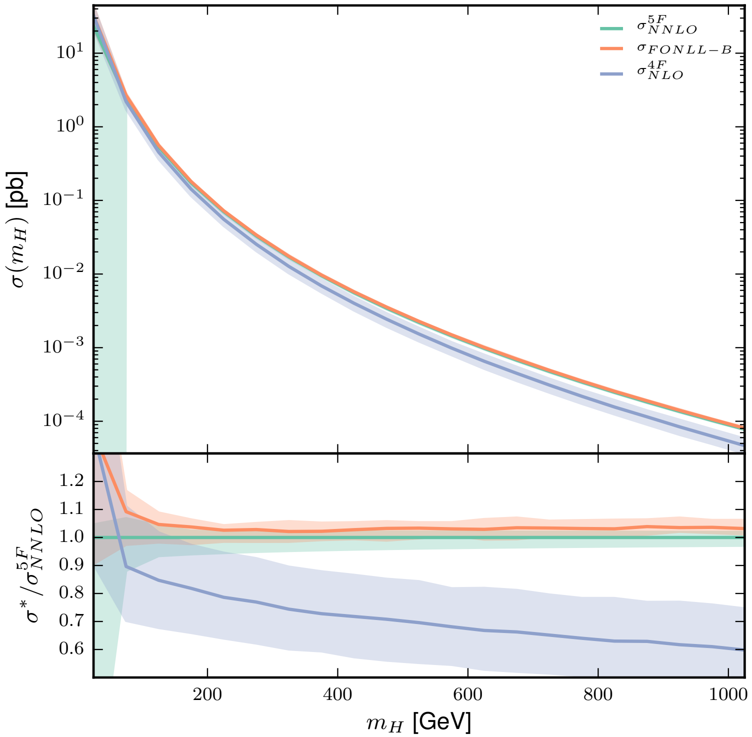




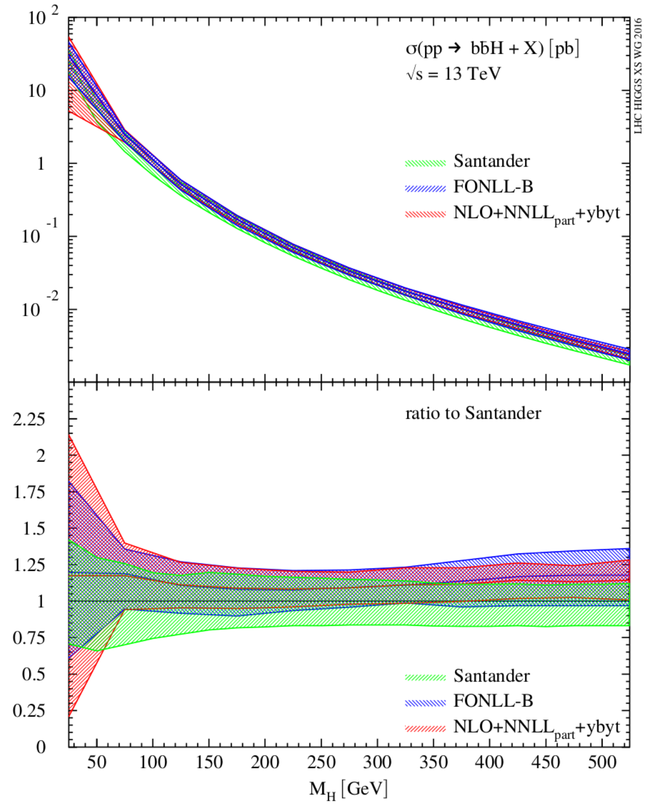
(SF, Napoletano, Ubiali, 2015-2016)

- SLOW CONVERGENCE AND STRONG μ_R DEPENDENCE OF MASSIVE SCHEME RESULT
- NLO MASSIVE CLOSER TO MASSLESS $\Rightarrow \ln \frac{m_h}{m_b}$ RESUMMATION DOMINANT
- FACTORIZATION SCALE DEP. STATIONARY FOR $\mu_f \sim Q_{\rm phys} \Rightarrow$ LOW $Q_{\rm phys} \sim m_h/4$
- MODERATE "MASS" CORRECTIONS

Higgs in bottom fusion
FONLL
Higgs mass dependence



(SF, Napoletano, Ubiali, 2016)



(HXSWG, YR4, 2017)

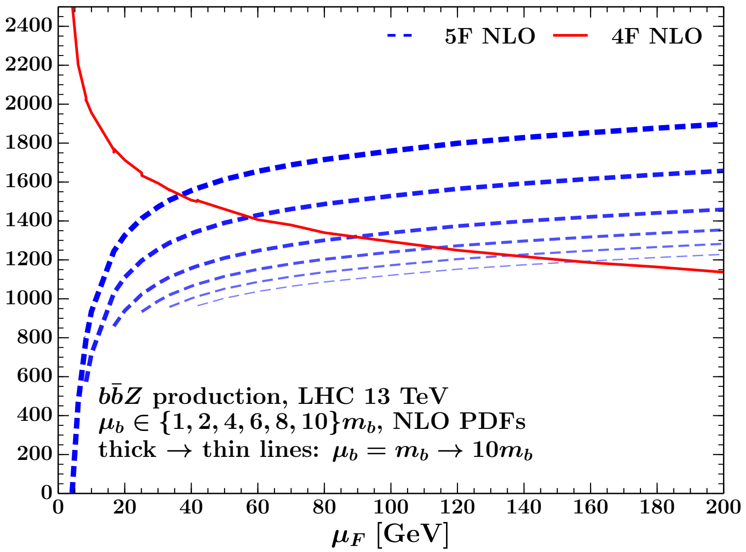
- FONLL quite close to massless, 5FS adequate FAPP, Santander bad approx
- FONLL-A - FONLL-B difference almost mass-indep $\Rightarrow$ (small) FONLL improvement $O(\alpha_s^3)$ constant (i.e. dep on $\tau = \frac{m_h}{s}$), indep of $\frac{m_b}{m_H}$
- agreement with SCET approach (Bonvini, Papanastasiou, Tackmann, 2016)

TUNING THE MATCHING SCALE?

- HIGH CHOICE OF MATCHING SCALE $\mu_m \sim 10 m_h$:(Mitov et al., 2017)
  - INITIAL HQ PDF PERTUBATIVELY ACCURATE
  - RESUMMATION OF HQ LOGS SUPPRESSED
- TOY CASE $b\bar{b}Z$ / $b\bar{b}H$:
  - 4FS & 5FS GET CLOSER AT HIGHER MATHCHING SCALE
  - BUT 4FS $\rightarrow$ STRONG μ_r DEPENDENCE, PERT. INSTABILITY
  - COMPARISON TO MATCHED: LOGS DOMINATE OVER CONST.

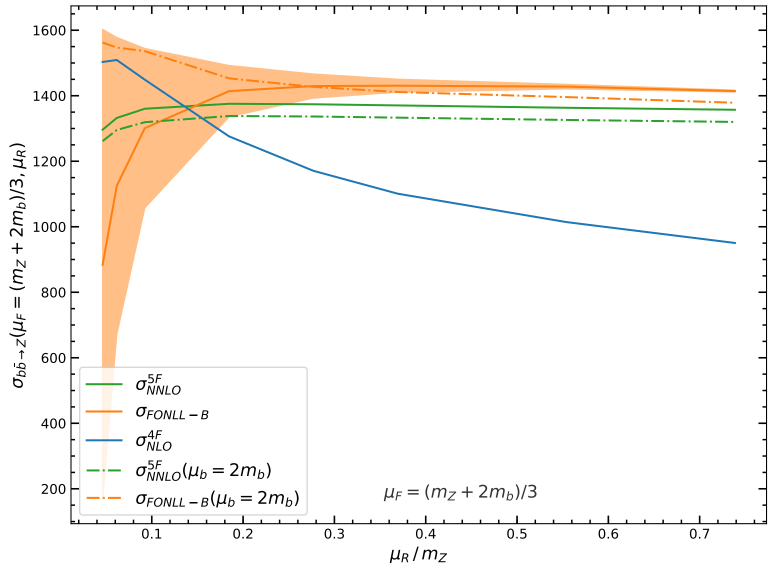
$Zb\bar{b}$

SCALE DEP. VS. MATCHING



(Bertone, Glazov, Mitov, Papanastasiou, Ubiali, 2017)

DEP. ON MATCHING SCALE



(SF, Napoletano, Ubiali, 2018)

PARAMETRIZED B AS A MASSIVE SCHEME

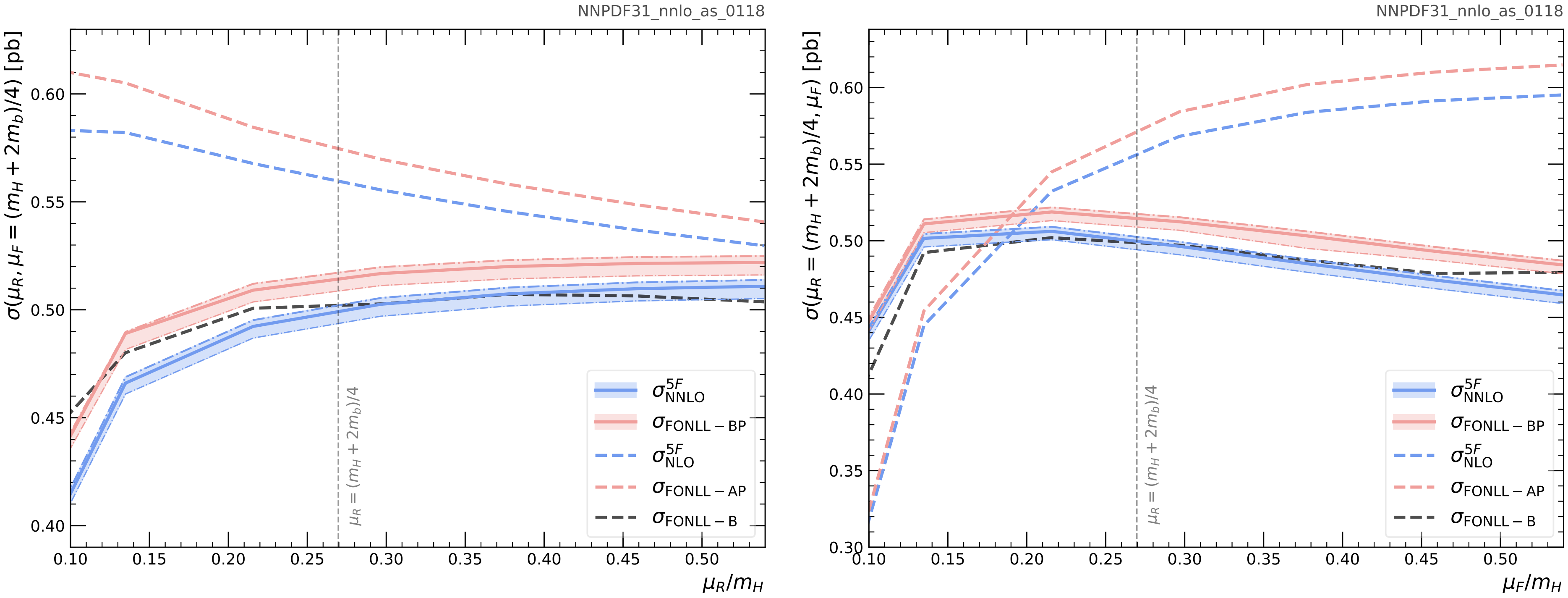
- PARAMETRIZED b PDF $\Rightarrow$ MASSIVE MATRIX ELEMENT WITH MASSLESS PDF AND MASS LOGS REMOVED
- 4FS (MASSIVE) STARTS AT $O(\alpha^0)$

$$\sigma^{\text{FONLL}} = \sum_{i,j}\sum_{l,m} \sigma_{ij}^{\text{massive}}\left(\frac{m_h^2}{m_b^2}\right) \otimes K_{il}^{-1} \otimes f_l^{(5)}\left(Q^2\right) K_{jm}^{-1} \otimes f_m^{(5)}\left(Q^2\right)$$

- FONLL-AP: MASSIVE $O(\alpha_s)$ (NLO); MASSLESS $O(\alpha_s^2)$ COEFF. FCTN, & SPLITTING FCTN (NLO)
- FONLL-BP: MASSIVE $O(\alpha)$ (NLO); MASSLESS $O(\alpha_s^2)$ COEFF. FCTN, & SPLITTING FCTN (NNLO)

$$\sigma^{\text{FONLL-BP}} = \sigma^{\text{FONLL-AP}} + \sum_{l,m} \sigma_{lm}^{(5),(2)} \otimes f_l^{(5)}\left(Q^2\right) f_m^{(5)}\left(Q^2\right)$$

Higgs in bottom fusion
FONLL with parametrized b



(SF, Giani, Napoletano, 2019)

- FONLL-B, FONLL-BP three curves shown $\Rightarrow$ b PDF as if using perturbatve matching at $m_b/2$, m_b, $2/3M_b$ (bottom to top)
- FONLL-BP, FONLL-B directly comparable: 1st two massive orders combine with massless NNLO
- FONLL-B: $gg \to bbH$; FONLL-BP: $\bar{b}b \to H$ (enhanced due to phase space)
- large negative correction when going from massless NLO to NNLO
- mass corrections same size as PDF dependence

SUMMARY

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